# ENGINEERING SEISMIC INVESTIGATION

# OF THE

# VILLAGE OF PAGUATE, NEW MEXICO

By

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## INTRODUCTION

This report summarizes the investigation of the levels of ground motion in the village of Paguate, New Mexico, associated with contained explosions detonated in an open-pit mine adjacent to the village (fig. 1). The report presents a general summary of the results together with discussion and preliminary conclusions. A final published report will be written pending review of this report summary by the Bureau of Indian Affairs, the Laguna Council, the Paguate Village Council and the U.S. Geological Survey.

The objective of the project is to investigate the possibility of building damage from man-made seismic sources, the probable distribution of the induced ground motion, and areas of high potental risk from vibration damage in the future. The report also suggests a procedure to help minimize the possibility of vibration damage to the structures of the village of Paguate, New Mexico, from future local industrial, cultural, or reclamation activities.

Induced ground motions from eight contained test explosions for this project that were located near the Jackpile open-pit mine were recorded at 29 locations in the village. The seismic data from the explosions were analyzed to establish the attenuation factors for the induced ground motion, the site response at pertinent locations from the induced ground motion, and the building response to the induced motion. Forty test borings and 25 shallow refraction surveys were made within the village to establish the near-surface

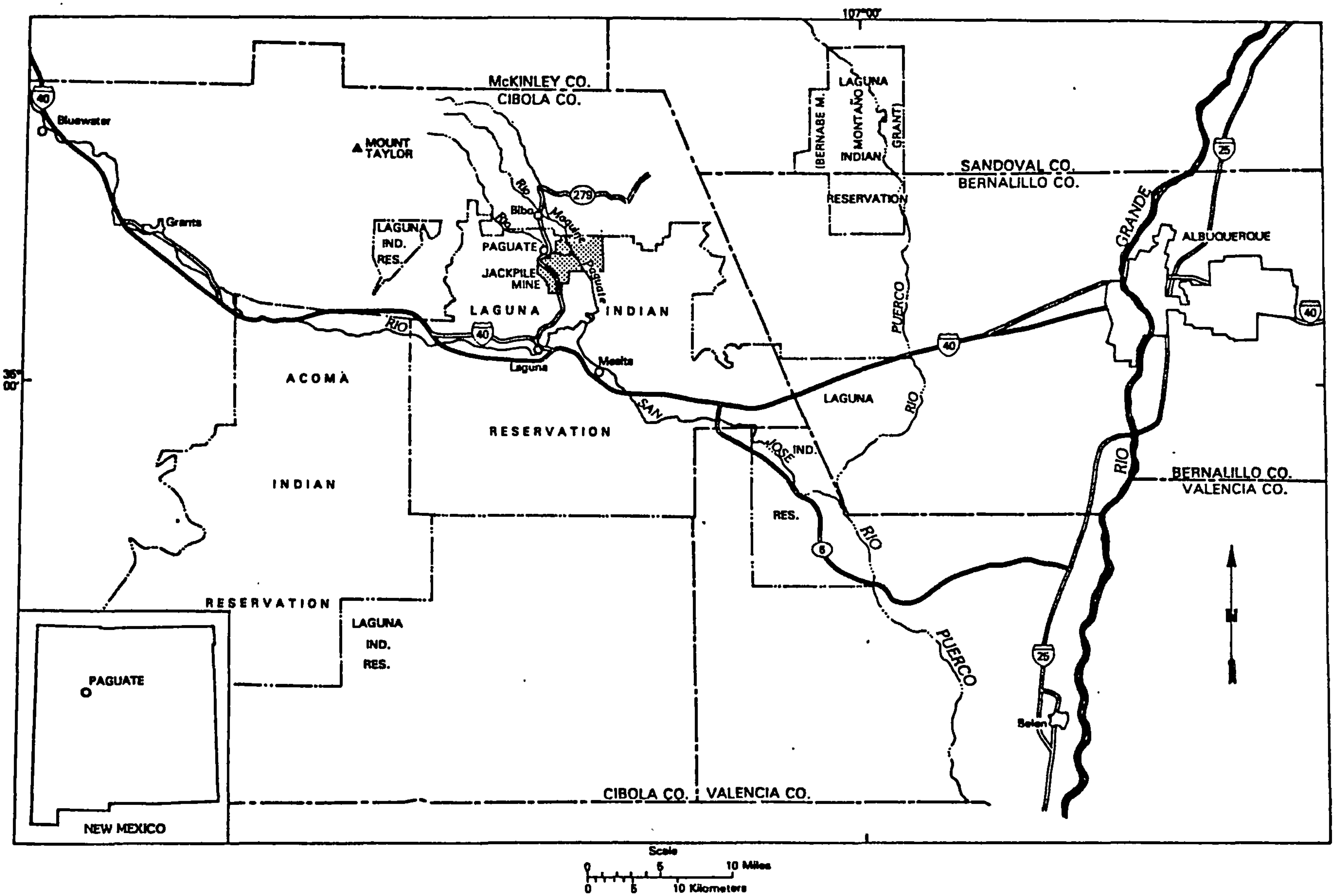


Figure 1.--Map showing location of the Jackpile Mine (shaded) and the village of Paguate, New Mexico.

site geology. The footings of 12 bearing walls of pertinent buildings were exhumed and inspected to investigate the possibility of differential compaction beneath the buildings. Over 95 percent of the buildings in the village of Paguate were inspected and evaluated according to the degree of existing damage. Similar damage inspections and evaluations were made on approximately 50 structures of similar type in other villages located in New Mexico in geologically similar areas but not located near quarries. Bearing walls of 21 buildings in the village of Paguate were tested to document the structures' natural vibration period and percentage of vibration damping.

## BUILDING INSPECTIONS AND TESTING

The first step in the investigation was to establish a method of comparing and mapping the building damage in the village. The predominant type of structure in the village is similar to the "Chaco"-or prehistoric native type (stone core with mud or adobe outer covering) rather than the "Spanish" adobe-brick type (King and Algermissen, 1985; Iowa, 1985). However, the buildings built within the village in the last 15 years are the standard stick-frame type, "Spanish" adobe type, or rehabilitated "Chaco" type. The village building inventory consists of approximately 60 percent of the native type (mud or stucco covered "Chaco" type), 10 percent adobe type, and 20 percent stick-frame type (the 25 HUD buildings bias the data to the stick-frame type). No trailers, temporary, or minor outlying structures were included in the inventory. Less than 5 percent of the buildings are totally native in internal and external construction; for example, most buildings have modern rafter and/or metal roofs.

The measurement or scaling of the degree of damage of the buildings is subjective; however, by sampling over 90 percent of the major buildings in the village and by having a large number (over 50 percent) of the buildings inspected and damaged scaled by more than one inspector, a workable statistical model and a general building damage map of the village was obtained. The damage scale used and the damage descriptions are shown in table 1. A building map shows the distribution of the building damage (fig. 2). Five buildings were rated at a damage degree of 5, 29 buildings rated a degree of 4, 85 buildings rated a degree of 3, and over 52 buildings rated a degree of 2. No buildings were found to have a rating of 1 in the village. The damage ratings assigned to the buildings may vary by one degree; however, all buildings rated at a 4 or 5 were inspected by at least two inspectors at different times. The damage map indicates that the buildings of higher damage are clustered in specific areas and are not randomly distributed over the village. The map also indicates that the areas of higher damage (in the northwest and the southwest areas) are located farther from the mine pit than are some buildings with lower degrees of damage. The map also indicates that the stick-frame houses, in general, show lower degrees of damage than the "Chaco" or adobe types.

The damping and natural resonant frequency of the buildings in Paguate are important parameters in the analysis of the response of the buildings to induced ground motion. A large number of the buildings are irregular, nonengineered structures which would be difficult to model to obtain these parameters. The test procedure for obtaining the damping and natural frequency of vibration generally consisted of installing horizontal, velocity motion-sensing seismometers on the top-midpoint of bearing walls of the structure (King, 1969). Ambient seismic background and the induced shaking from a number of the test explosions are then recorded (fig. 3). The induced vibrations recorded in this study were man-induced. The induced forces were

Table 1.--Damage scale for adobe/rock structures

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Degree 1

Light visible cosmetic cracking in the interior and/or exterior. Cracks less than 1 mm wide.

Degree 2

Visible 2 or less wide cracks in the interior and exterior. Fine cracks (less than 2 mm) near windows, doors, and support members.

Degree 3

Visible 2 to 5 mm wide cracks which extend from or connect points of stress. Length of cracks exceeds 10 cm. Erosion of cracks may be present. Light structural damage is possible (ceiling or viga cracking, door or window framing distorted, etc.).

Degree 4

Visible 5 to 12 mm wide cracking with length over 10 cm. Slight cracking through width of wall. Large amount of 2 to 5 mm cracking. Cracking recurring through past repairs into original construction. Distortion or evidence of movement of structural members. Moderate structural damage present.

Degree 5

Visible damage (cracking, movement, distortion) present on interior and exterior walls. Cracks larger than 5 mm through thickness of wall. Extensive cracking including a moderate amount larger than 12 mm wide and exceeding 10 cm in length. Major distortion or movement at stress concentration points (window, doors, roof supports, wall supports, etc.).

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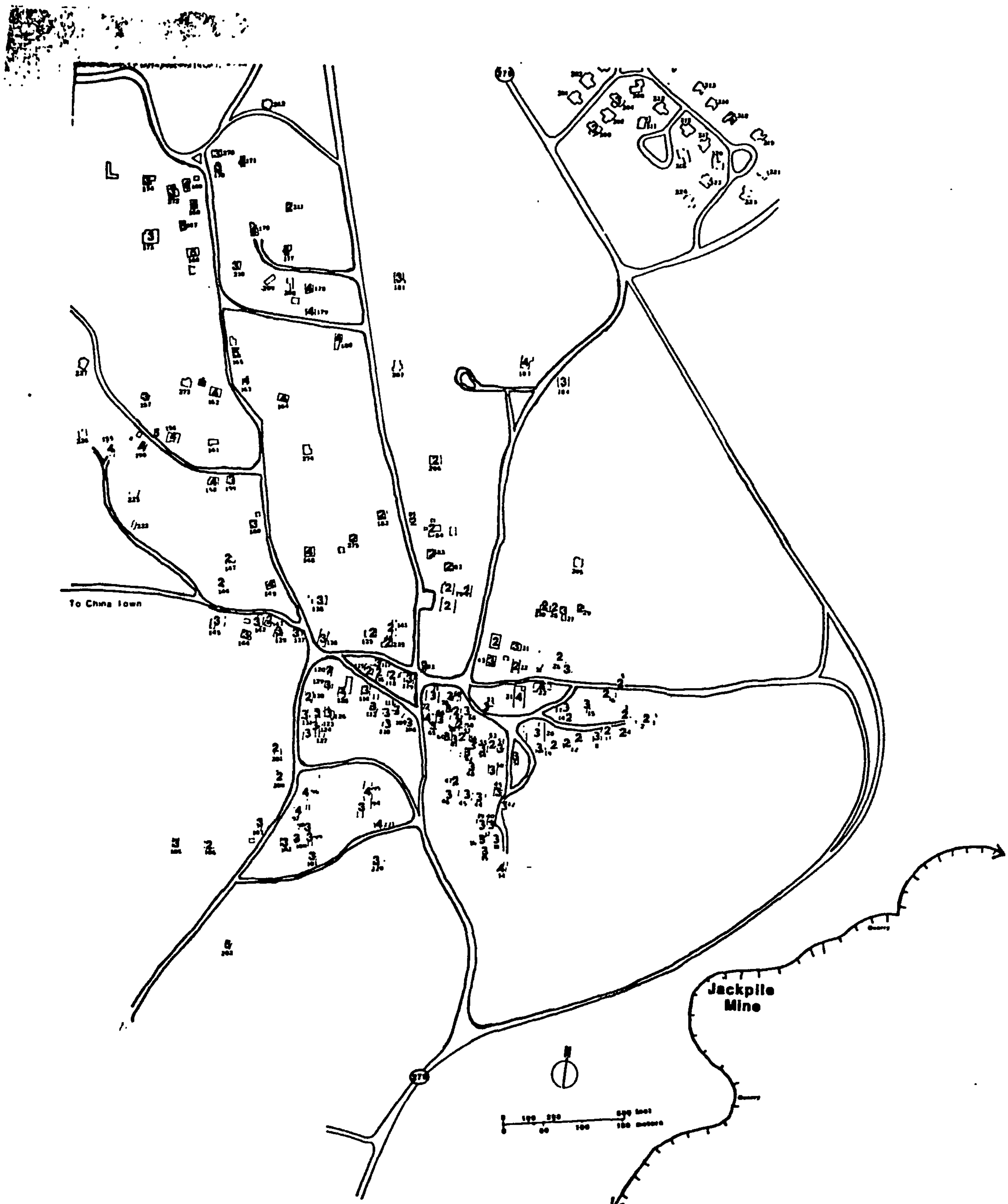


Figure 2.--Map showing the village of Paguate and the distribution of building damage using the scale shown in Table 1. Degree of damage shown by large numbers. Small number adjacent to the building is used to identify that structure in the text.

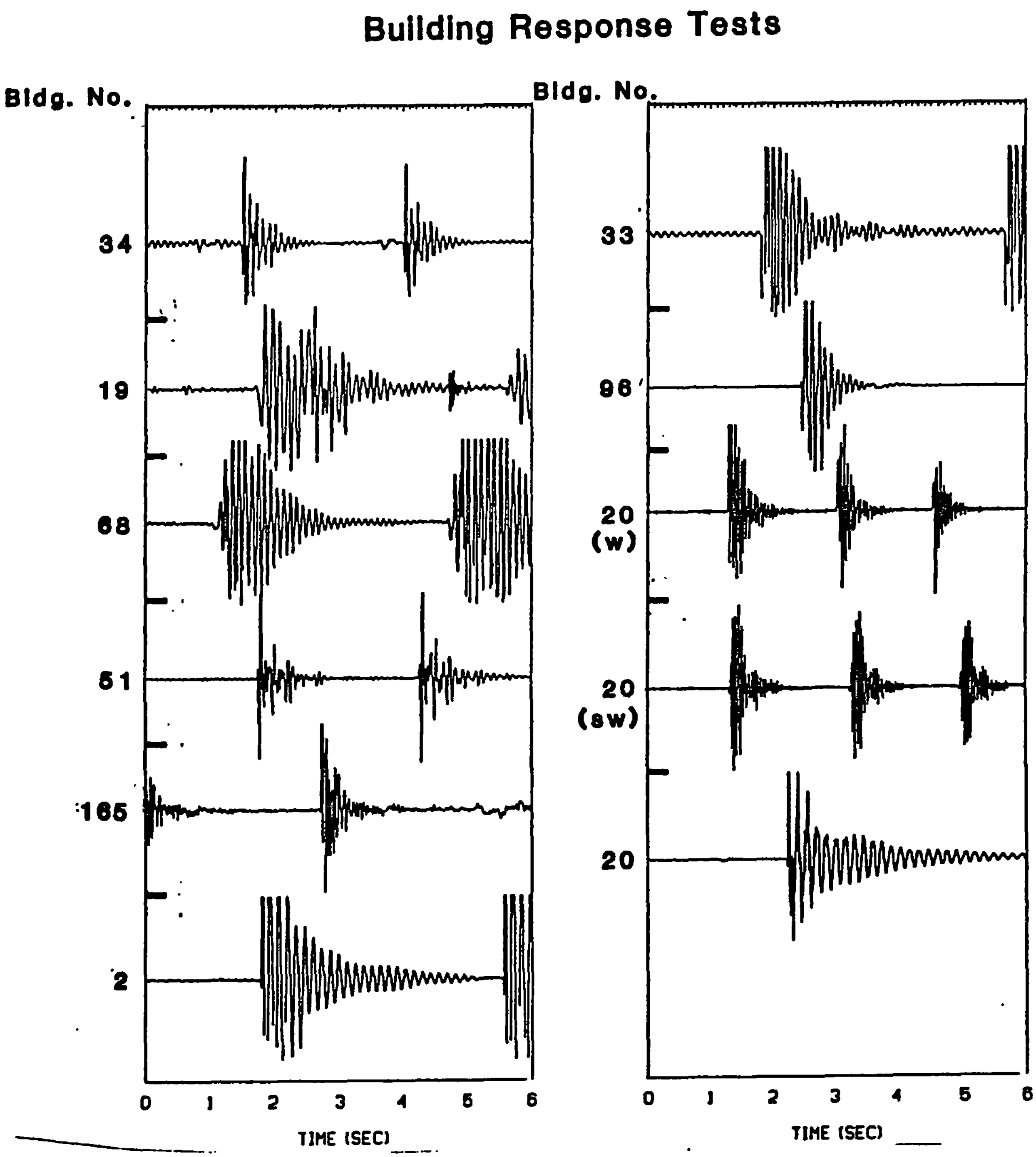


Figure 3.--Time-histories for man-induced vibrations measured on the top-midpoint of the bearing walls for the buildings listed on the left of the seismic record.

input in close synchronization with the structure's approximate natural resonant frequency. This technique has been described in detail by Hudson and others (1964) and King (1969).

The data from the tests were analyzed to determine the response of the walls to induced motions, the natural periods of the walls, and the damping factors of the walls. The data were analysed to obtain the approximate percentage of critical damping using:

$$\beta = \frac{1}{2\pi} \left(-\ln \frac{Xn + 1}{Xn}\right)$$

where $\beta$ is the percent critical damping and Xn is the velocity amplitude for the nth cycle of motion. The natural periods of the walls were picked as the peak of the response spectra (fig. 4). The natural frequencies varied from 5 to 14 Hz with damping varying from 1.5 percent to approximately 9 percent (table 2). The periods and damping values are in the normal range for the "Chaco"-type structures (King and Algermissen, 1985).

Villages that are located away from a quarry, mine, road building, or other blasting activities have similar type buildings as the village of Paguate and are underlain by 1-20 feet of sediments similar to Paguate could not be found. The 50 similar type buildings (30 buildings of "Chaco"-type construction and 20 buildings of mixed adobe, stone, and stick-frame construction) that were inspected for comparisons are in the villages of San Felipe and Santo Domingo. The villages are located away from blasting-type activity, but since the villages are located on a river wash area, they are probably underlain by unconsolidated sediments that are high in clay-silt content (greater than 60 percent) and are thicker than 15 feet. The percentage damage-scaled degree grade comparison between the village of Paguate and comparison villages are shown on table 3.



 

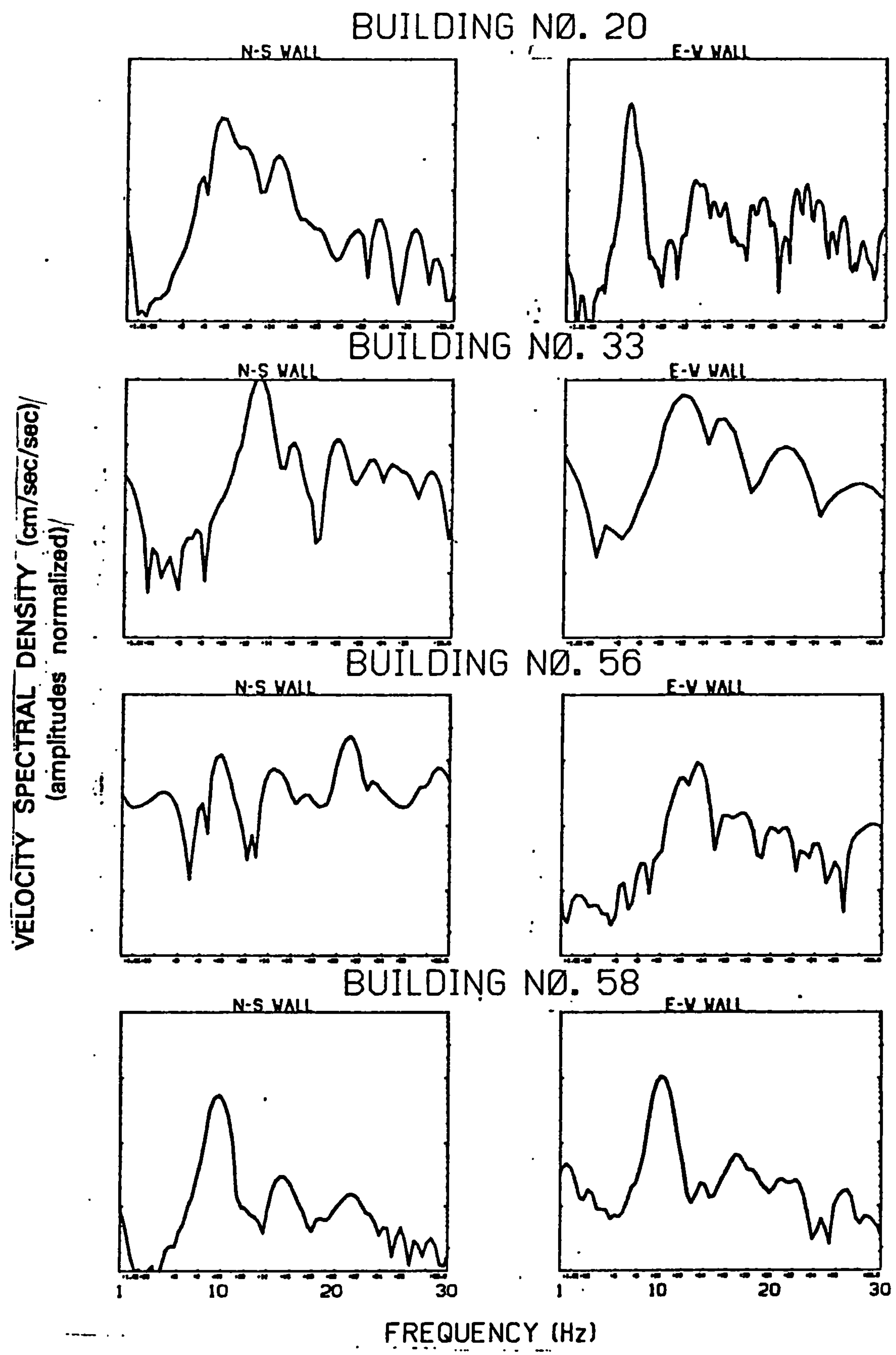


Figure 4.--Normalized spectra for north-south and east-west walls of 4 buildings. Spectra are derived from recordings of man-induced seismic energy applied directly on the walls.

Table 2.--Building vibration tests

| Building no. | Bearing wall | Natural frequency (Hz) | Percent damping | Site response function |
|---|---|---|---|---|
| 2 | West | 16.7* | 2.8 | |
| | North | 5.7 | 3.2 | |
| 19 | West | 12.2 | --- | |
| | South | 11.0 | 1.6 | |
| 20 | West | 10.0 | 1.9 | |
| | North | 6.8 | 2.5 | |
| | East | 9.6 | 2.8 | |
| | South | 10.9 | 1.6 | |
| 33 | West | 12.8 | 4.1 | |
| | East | 12.9 | 3.0 | |
| | South | 12.2 | 3.7 | |
| 36 | East | 15.5 | 3.9 | |
| | South | 14.0 | 5.6 | |
| 37 | North | 6.4 | 5.6 | |
| | East | 11.3 | 4.5 | |
| 38 | West | 8.0 | 5.6 | |
| | North | 5.3 | 4.1 | |
| 51 | East | 10.2 | 1.8 | |
| | South | 10.5 | 4.8 | |
| A51 | West | 9.2 | 6.9 | |
| | South | 5.3 | --- | |
| 56 | North | 13.4 | 1.8 | |
| | East | 9.7 | 2.4 | |
| 58 | North | 10.1 | 2.9 | |
| | East | 9.7 | 3.9 | |
| 95 | North | 12.5 | 3.1 | 2.5 |
| | East | 11.2 | 2.9 | |
| 96 | West | 9.8 | 3.2 | 3.1 |
| | North | 9.8 | 3.8 | |
| 130 | East | 9.4 | 2.4 | 2.5 |
| | South | 11.3 | 1.9 | |
| 164 | East | 3.7-9.8 | 5.8 | 2.9 |

Table 2--(Continued)

| Building no. | Bearing wall | Natural frequency (Hz) | Percent damping | Site response function |
|---|---|---|---|---|
| 165 | West | 8.2 | 7.8 | 2.0 |
| | North | 10.6 | 6.9 | |
| 165A | South | 8.2 | 7.0 | 2.0 |
| | West | 11.3 | 7.0 | |
| 167 | North | 12.6 | 3.4 | |
| | East | 9.0 | 2.7 | |
| | South | 10.3 | 3.7 | |
| 168 | North | 18.1 | 1.6 | |
| | East | 9.6 | 2.9 | |
| | South | 17.2 | 2.4 | |
| 179 | West | 9.5 | --- | |
| | North | 10.6 | --- | |
| 184 | East | 10.2 | 3.4 | |

Table 3.--Village damage comparison

| Scale | Paguate % | Villages % |
|---|---|---|
| 1 | 0 | 10 |
| 2 | 30 | 62 |
| 3 | 48 | 22 |
| 4 | 18 | 4 |
| 5 | 3 | 2 |

## Test Borings and Pits

Forty test borings were completed within the village of Paguate together with 25 shallow refraction surveys. The locations of the test borings and refraction lines are shown in figure 5. The data from the borings and the refraction lines were used to map the thickness of the low seismic velocity material underlying the village. Ten core samples 5-10 inches (2-5 cm) in length were recovered from the boreholes. The core samples were analyzed for grain size, sand/clay ratios, void percentages, and any evidence of a perched or changed water table (staining, water content, etc.) (table 4). The percent core recovered versus percent cored was documented. The core loss due to compaction and the void ratios give an indication of the differential compaction potential. Sections of the foundations under a damaged bearing wall were exhumed and inspected for evidence of distortion and/or displacement.

Of the test borings, thirty were made to measure the thickness of sediments and soils over the bedrock underlying the village. The data from the borings along with the refraction-survey results show that the thickness of the unconsolidated sediments and/or materials with a propagation velocity

# PAGUATE SEISMIC STUDY

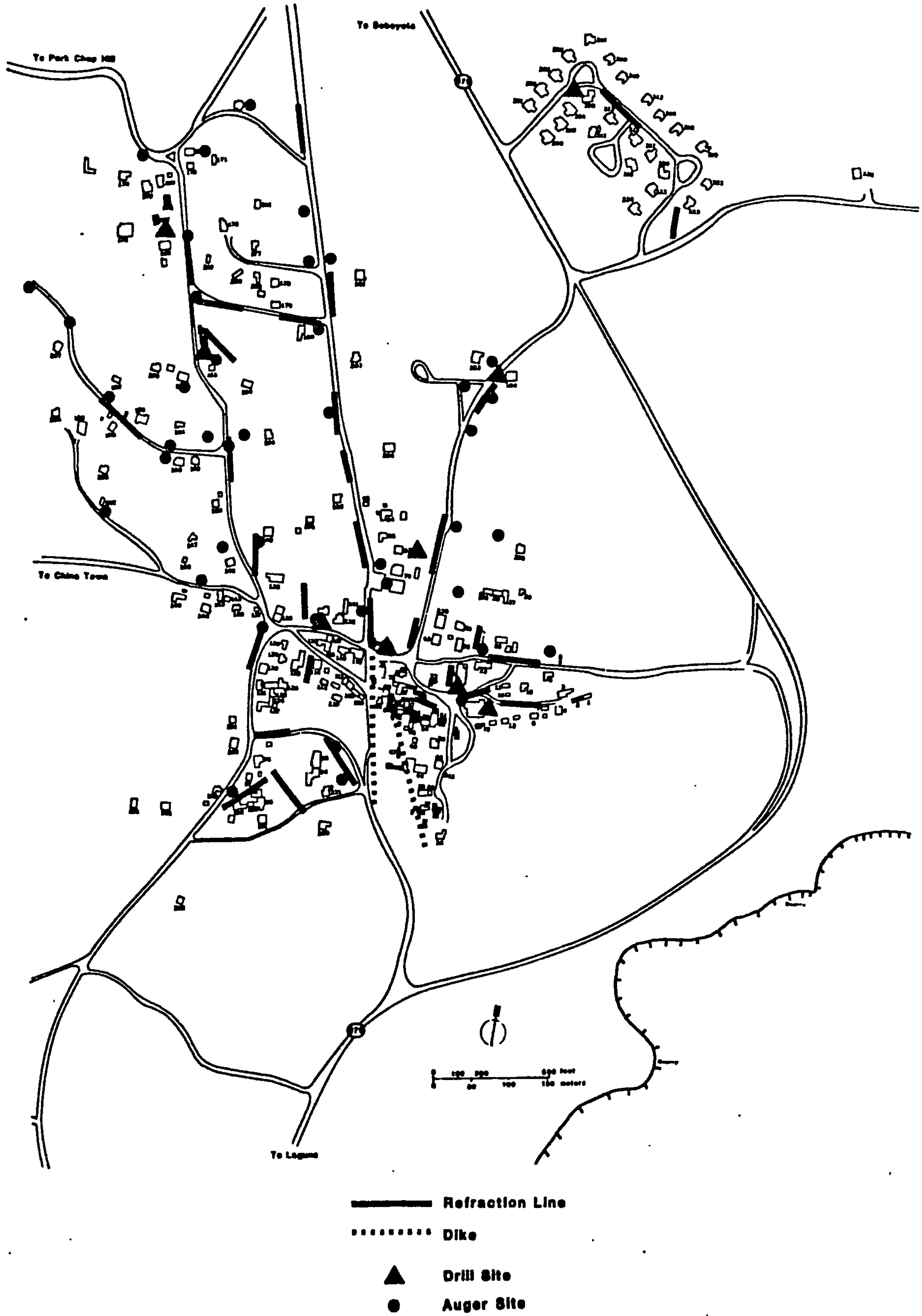


Figure 5.--Seismic study in the Paguate area showing drill and and auger test locations, lines of refraction and alignment of exposed rock dikes.

Table 4.--Soil sample test results

| Site no. | Average depth | Sand 4.76-0.075 (mm) | Silt 0.075-0.005 (mm) | Clay .005 (mm) | Stain | Percent recovered | Grain densit (gm/cc |
|---|---|---|---|---|---|---|---|
| 16 | 10 cm | 65.88 | 20.22 | 13.87 | Brown | 100 | 2.71 |
| 20 | <10 cm | Rock | --- | --- | --- | | |
| 21 | <10 cm | Rock | --- | --- | --- | | |
| 82 | 10 cm | 67.81 | 22.42 | 9.74 | Brown | 98 | 2.77 |
| 93 | 10 cm | 58.43 | 30.43 | 11.13 | Brown | 95 | 2.84 |
| 165 | 10 cm | 44.06 | 36.14 | 19.80 | Brown | 96 | 2.74 |
| 167 | 10 cm | 52.12 | 35.46 | 12.42 | Brown | 95 | 2.73 |
| 184 | <10 cm | Rock | --- | --- | --- | | |
| 308 | 10 cm | 55.34 | 37.45 | 7.21 | Brown | 95 | 2.76 |
| 165 | 1 m | 43.87 | 44.05 | 12.08 | Y | 100 | 2.78 |
| 167 | 1 m | 50.32 | 35.52 | 14.16 | Y | 98 | 2.84 |
| 165 | 2 m | 61.26 | 23.66 | 15.08 | Y | 98 | 2.88 |
| 167 | 2 m | 48.58 | 41.77 | 9.65 | Y | 96 | 2.85 |

of less than 3,500 ft/s (1,066 m/s) overlying the sandstone bedrock varied from less than 1 foot (.3) in the general area of building 6 to over 15 feet (4.6 m) thick in the areas of buildings 164, 206, and 220 (fig. 6). The thickness of low propagation velocity underlying material exceeds 15 feet in the area of "China Town" and the area west of the village in the drainage valley. Test cores were made to a 24-inch (.6 m) depth near buildings 16, 20, 21, 82, 93, 165, 167, 184, and 308. The coring was inconclusive at buildings 20, 21, and 184 as bedrock was less than 24 inches deep. The core compaction of the cores recovered at the remaining sites was less than 5 percent which gives a general indication of a low compaction susceptibility. A mean void ratio was computed for the samples from site 165 and 167 by the relation VR = (GS/GD)-1 where VR is the void ratio, GS is the dry-density and GS is the density of the material without the voids. Core samples were recovered at 4-foot (1.2 m) and 6-foot (1.3 m) depths at buildings 165 and 167. The mean void ratios at the sites tested varied between 0.55 and 0.65. The highest void ratio calculated was 0.65 at 24 inches (.6 m) depth at building 16. No hydrological data or obvious water-induced staining or precipitation, which may indicate a changed water table, were detected in the core samples or bore holes.

A 2 to 3-foot (.6 to .9 m) section of the foundation supporting a bearing wall was exhumed at buildings 165 (two walls), 167 (two walls), 34 (one wall), 36 (one wall), 220 (two walls), 179 (two walls), and 202 (two walls). All buildings except 34 and 36 had at least 18 inches (.45 m) of footing material (rock and/or concrete) under the walls. The foundations of buildings 34 and 36 are located on sandstone bedrock. The inspections of the foundations indicated no discernible displacements. The test pits were located beneath large cracks in the walls of the buildings which did not visibly continue

# PAGUATE SEISMIC STUDY

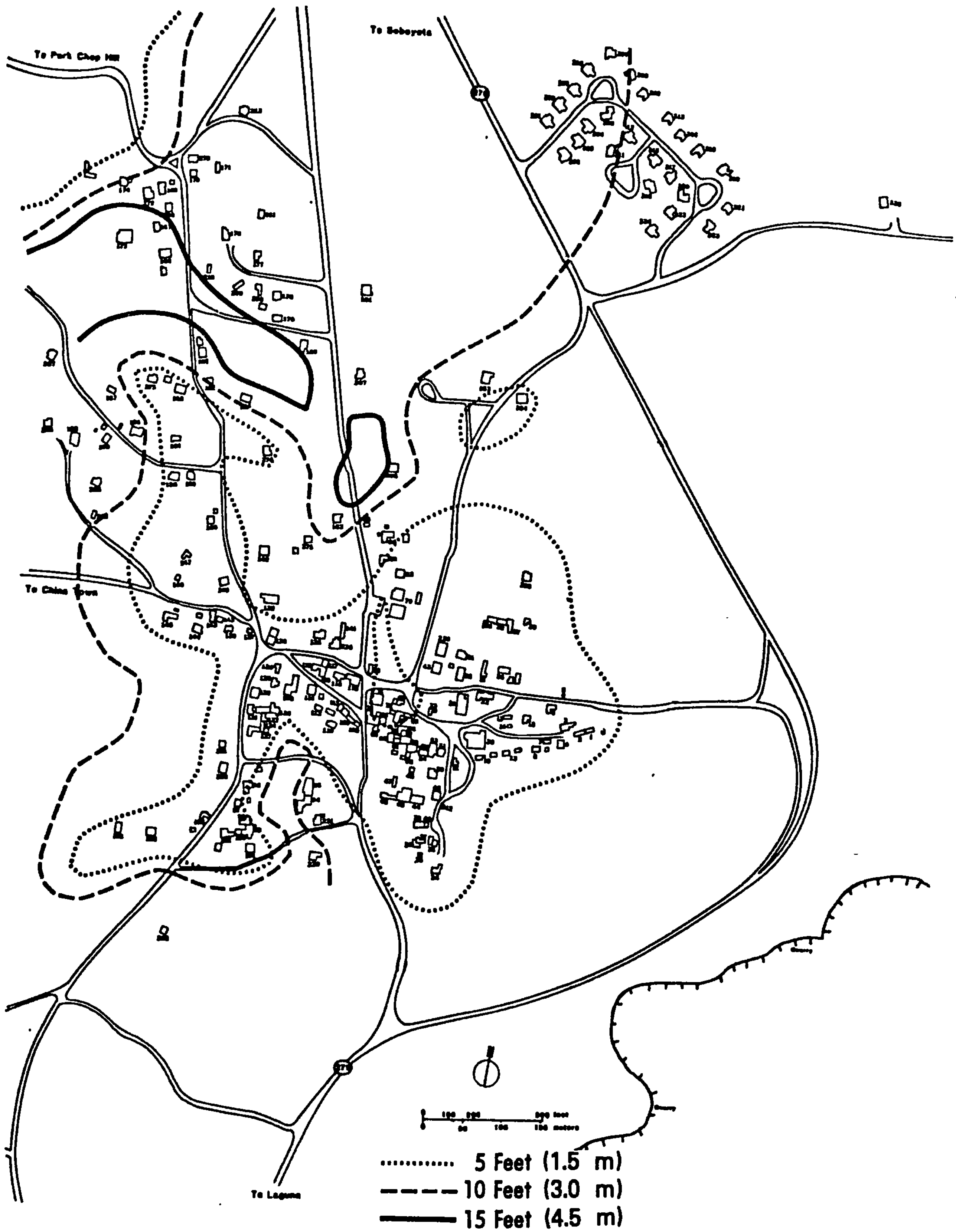


Figure 6.—Contour lines showing the thickness of low velocity (seismic propagation velocity) materials as measured by seismic refraction methods and auger holes. Low velocities are those less than 3500 ft/s (1066 m/s).

through the foundation exposed in the test pits at buildings 165, 167, 179, and 220. The foundation inspection at building 202 is inconclusive. Displacements and/or cracks could have been present in the foundation exposed by the test pit at building 202, but due to the friable nature of the soil in the test pit, the foundation could not be seen in a non-disturbed condition.

## TEST EXPLOSIONS

Induced ground motions from eight test explosions were recorded at pertinent sites in the village. Each test explosion consisted of 100 pounds (45.4 kg) of ammonium nitrate/fuel oil mixture in a 60-foot (15.2 cm) deep, 6-inch-diameter borehole. The explosive mixtures were tamped with soil to the surface and all blasts were contained. Seven explosions were located east of the village on Laguna Reservation property again near the west wall of the Jackpile quarry and one event was south of the village on Laguna Reservation property near the west wall of the Jackpile quarry (fig. 7). The tests were a part of the investigation that was designed to compare the peak particle-velocity ground motion and velocity spectra at several pertinent sites in the village. The rate at which ground motion decreases with distance from the source (attenuation), the way that individual sites respond to the induced ground motions (site response), and the response of selected buildings to the ground motions (building response) were analyzed using the seismic data from the test explosions. Five portable engineering-seismograph systems, each with three orthogonal, velocity-sensing seismometers were used to record the ground-motion data from each test explosion.

Ground-motion attenuation with distance from the explosion was calculated. The seismic data that were used for this calculation were obtained from sites that are underlain by bedrock (to minimize the site

## PAGUATE SEISMIC STUDY

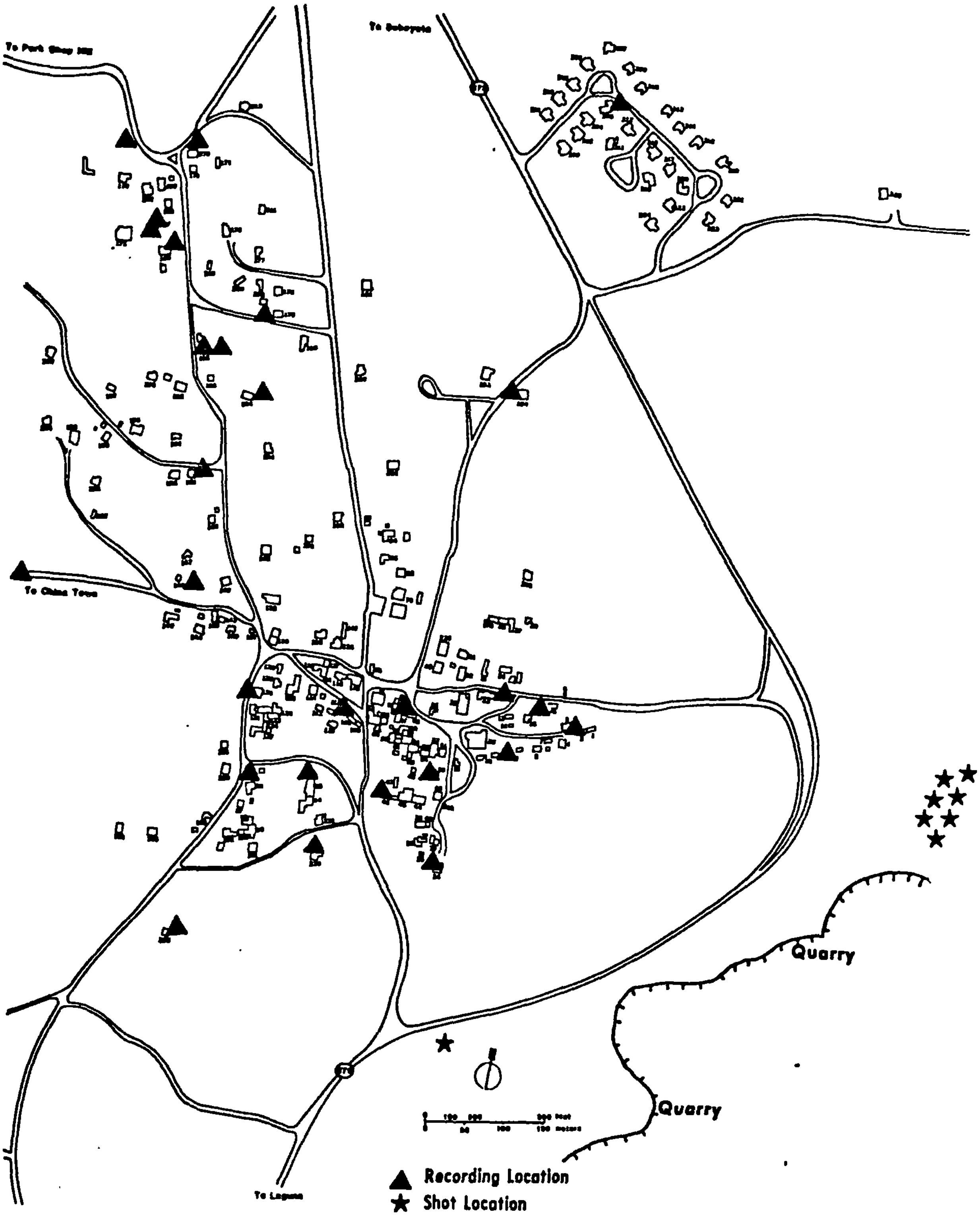


Figure 7.--Seismic study in the Paguate area showing shot and recorder locations.

response effects) and at similar bearings but in different distance ranges from the source (from 2,150 to 5,240 feet; 655 m, 1,047 m). Analysis of the seismic data induced from the explosions (figs. 8 and 9) yielded the peak particle and velocity spectral ground motion attenuation values throughout the village. An equation of the form of A = cR where A is the amplitude in cm/s (peak particle ground motion in velocity) or cm/s/s (spectral velocity density), c is a constant, and R is the explosion-to-site distance that was used to fit the attenuation data to the equation by least-squares regression. The relationship obtained is $A = cR^{-1.87}$ for peak particle, vertical ground-motion velocity and $A = cR^{-1.15}$ for peak particle, horizontal ground-motion velocity. The ground-motion, spectral-velocity, attenuation-scaling functions are similar to the peak particle scaling function except that the spectral attenuation is scaled for a range of frequencies between 1-15 Hz (fig. 10).

Portable engineering seismograph systems were operated near building 146 and/or building 6 on each test explosion. The recordings at these sites were used as the standard for comparison with the recordings from all of the other sites. Site 146 was chosen because it is underlain by bedrock (sandstone). The explosion-induced ground motions recorded on bedrock will not be affected or modified by overlying layers of unconsolidated sediments or soil. The site response on competent bedrock is assigned a ground motion amplification factor of 1 which assumes that the site does not amplify the induced ground motion from the source. Site 146 is also at a similar range from the test explosions as are several buildings that have a damage-scale degree of 4 to 5. Site 6 is used as a reference because the site is located nearer the test explosions than most of the buildings in the village and the building at this site has a damage-scale degree of 2.

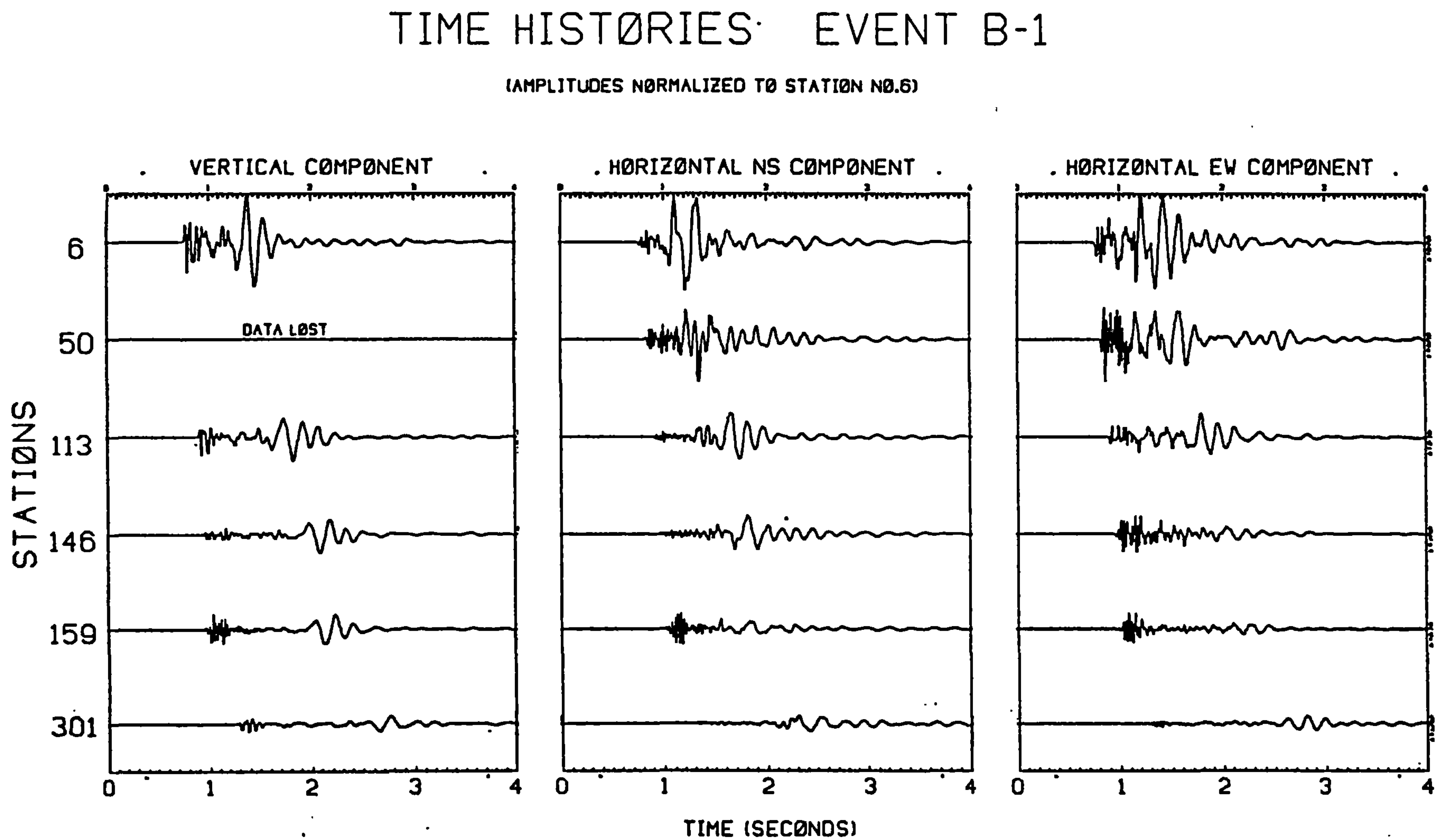


Figure 8.--Three-component time-histories of the test explosions recorded at 6 buildings in the village of Paguate.

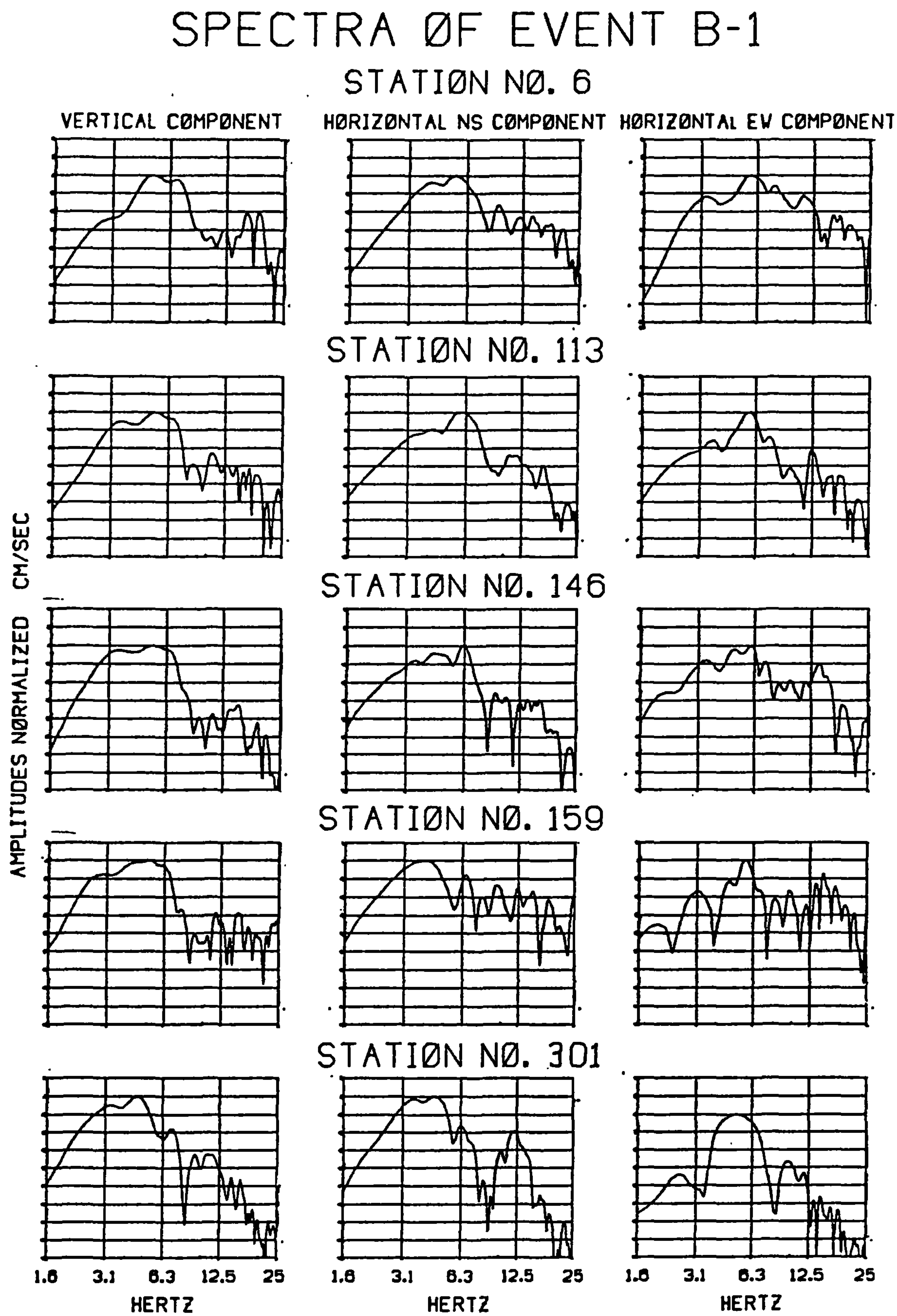


**Figure 9.--Spectra generated from time-history recordings of test explosions.**

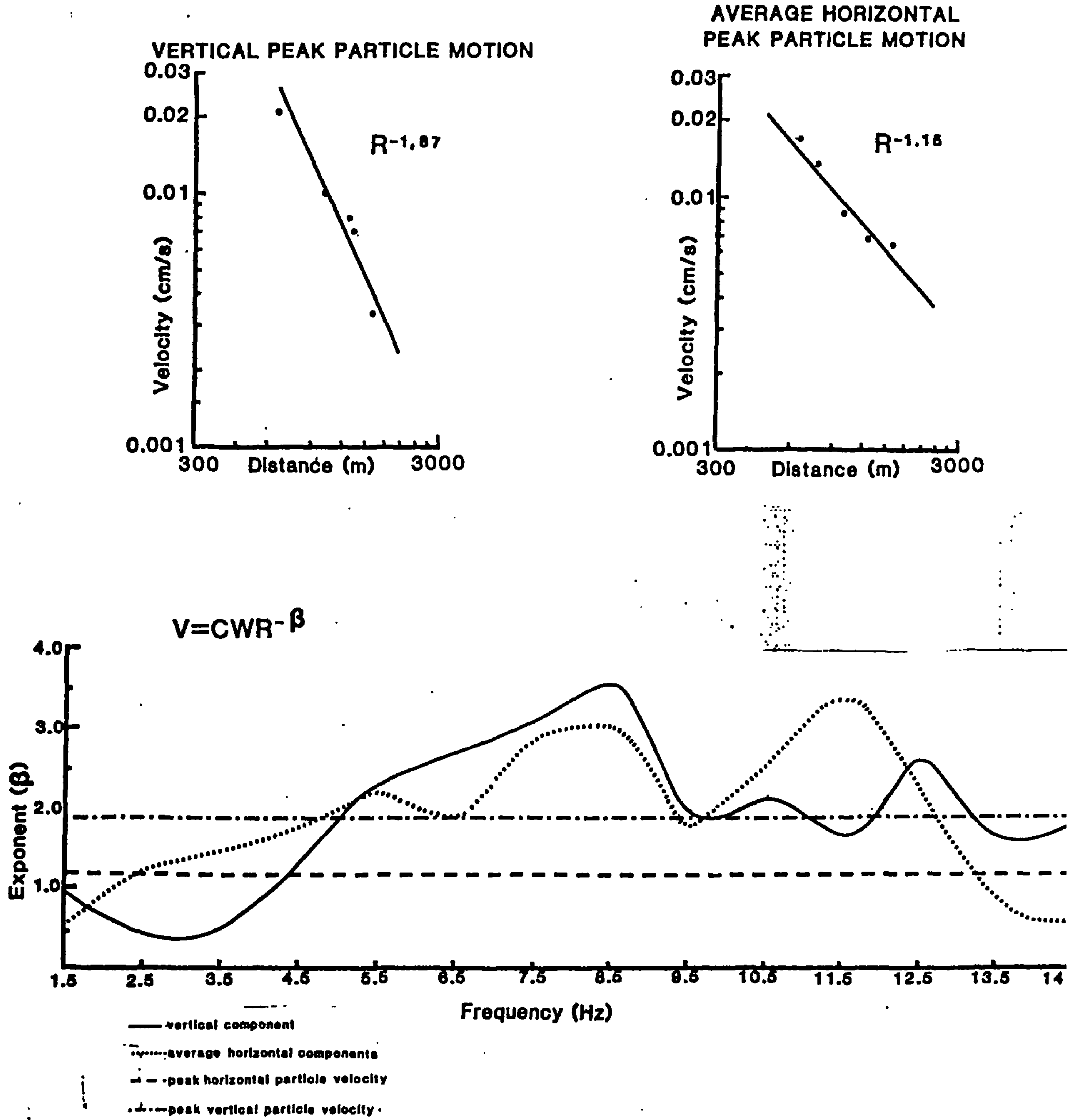


Figure 10.—Upper two graphs show the attenuation data. Bottom graph shows the attenuation for the average horizontal and vertical components where V = ground motion in cm/s; C = constant; W = yield in pounds; R = distance from the event in meters; $\beta$ = slope of regression line.

The spectra derived from the ground motions recorded at sites 6 and 146 from the test explosions east of the village are also used to calibrate the variations of the input sources. The highest and lowest spectral values at these sites are shown on figure 11a. The difference between the spectra are small since the test explosions were of the same approximate size, distance, and bearing from the recording sites. A similar comparison is made for sites 6 and 68 to document the variations of the input sources which are located east of the village against the input sources of the event located south of the village (fig. 11b). The ground motion variation due to difference in bearing of the test explosions shown on figure 11b is larger than that on figure 11a due to the larger difference in the distances from the events; however, the general spectral shape is similar. The comparisons indicate that the data from the east test explosions are, in general, comparable from one event to another. The comparison of the events at different bearings indicate that within the bearing variations that were tested, there were no large variations in the recorded ground motions associated with azimuth.

The spectral ratios between the rock site and site 164 (damage rating of 4) show that there is a site amplification of the horizontal ground motion at site 164 in the frequency band of 3.8-10.1 Hz. The peak site amplification of the east-west horizontal component of ground motion at this site is 5.1 at 6.2 and 8.9 Hz. The peak site amplification in the north-south horizontal component is 2.9 at 10.9 Hz (fig. 12). Site 165 (damage rating 5) is 350 feet (107 m) farther from the source than the rock site and also shows a site amplification. The site amplification of the horizontal ground motions at site 165 peaks at a factor of 8.2 at 6.4 Hz in the east-west component and a factor of 3.1 at 13.2 Hz in the north-south component (fig. 13).



 

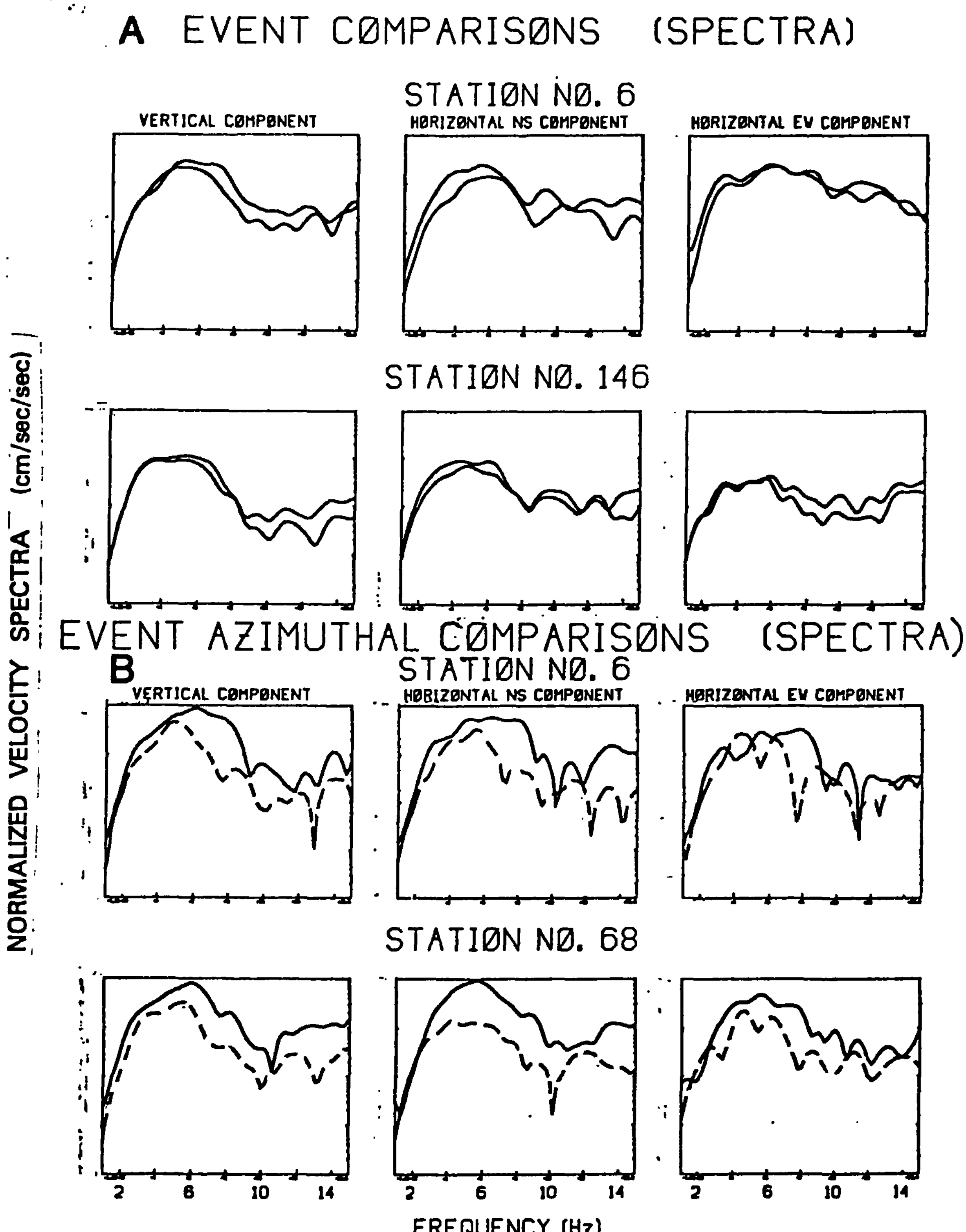


Figure 11.--(A) Test explosion variations are small as shown by the small variation in the ground motion spectra. The highest and lowest spectral values recorded at site 6 and 146 are shown. (B) Shows the variation in spectral values obtained from explosions east of the village (solid lines) to those south of the village (dashed lines).

The recorded ground motions from the sites in the village were compared to the seismic data recorded at the standard rock site (146) and/or the close-in low-damage site (6). The comparisons are made by taking the ratio of the spectra at any site to that at the standard site. The spectral ratios (SR) are calculated by: SRf = SCf/SSf, where f = frequency in Hz, SS = standard site spectra (146 or 6), SC = site being compared. The spectral amplitudes and the site transfer functions show the frequencies that are amplified at that particular site. The site transfer functions to the close-in low-damage site shows the frequencies at which amplification occurred at various distances from the explosions. The analysis of the test explosion data at the village sites, in comparison to the standard rock site and the low damage site, show that most of the sites investigated have ground motion amplification due to the site response and that the amplification is frequency dependent. Amplification of ground motion associated with the geotechnical properties of underlying soils has been documented as a phenomonon by a number of authors (Gutenberg, 1957; Kanai, 1952; Borcherdt, 1970; Hays and others, 1978; Rogers and others, 1978; and King and others, 1983, 1986).

Figure 14 shows the comparisons (ratios) of the spectra between the rock site and several other sites in the village. The ground motion on bedrock can be predicted for the sites in the village and/or factored to the bedrock station based on the attenuation functions calculated in the previous section. The seismic data from several sites in the village were normalized by using the average attenuation functions with the following equations: $Ac/As = (Rc/Rs)^{-1.87}$ for the vertical component and $Ac/As = (Rc/Rs)^{-1.15}$ for the horizontal component where Ac is the velocity value at the site being compared, As is the velocity value at the standard site (rock site or low damage site), Rc is the distance from the source of the site being compared,

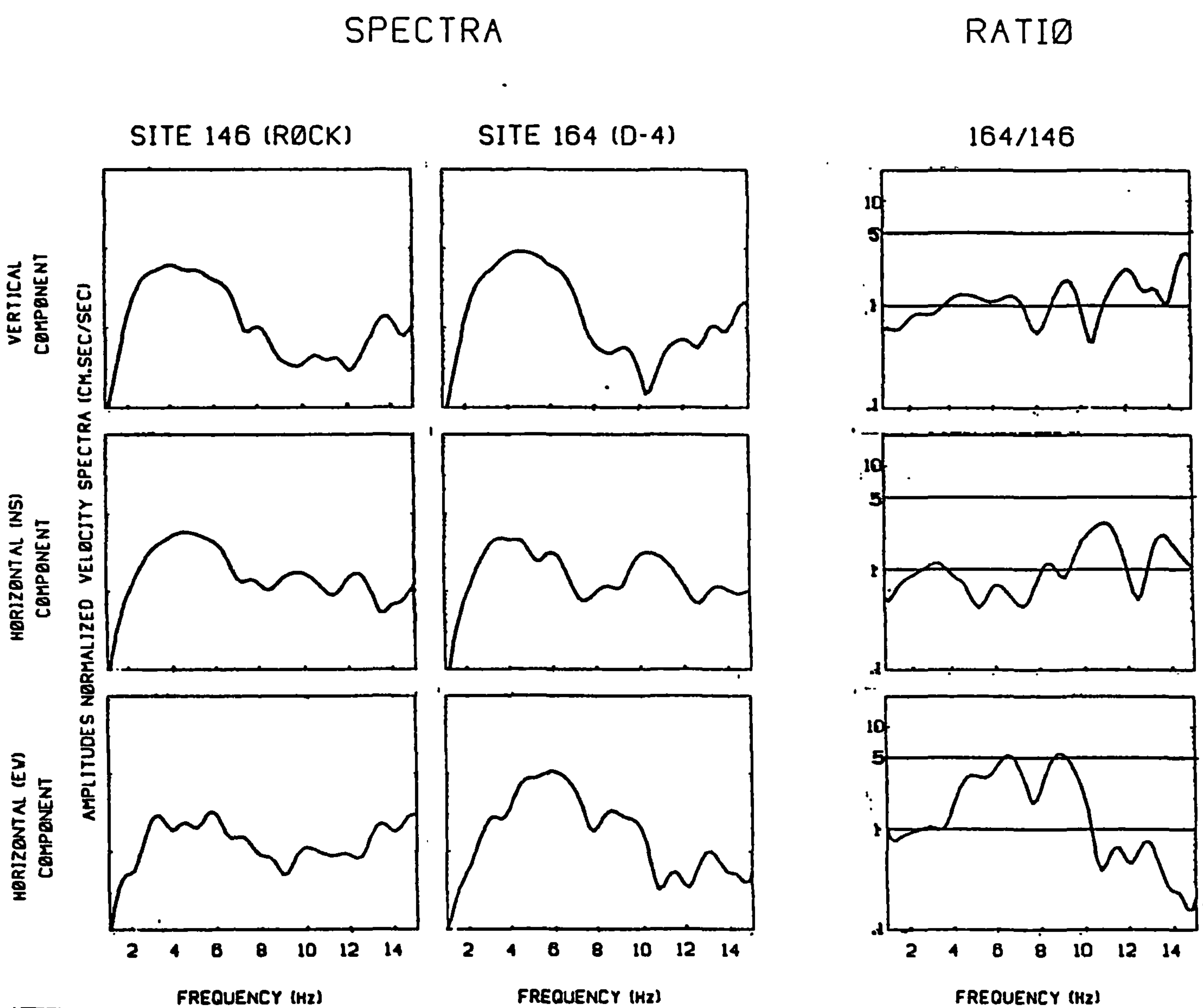


Figure 12.--The spectra of three components of ground motion and their accompanying ratios (164/146) show amplification of ground motion at site 164, especially in the east-west horizontal component.

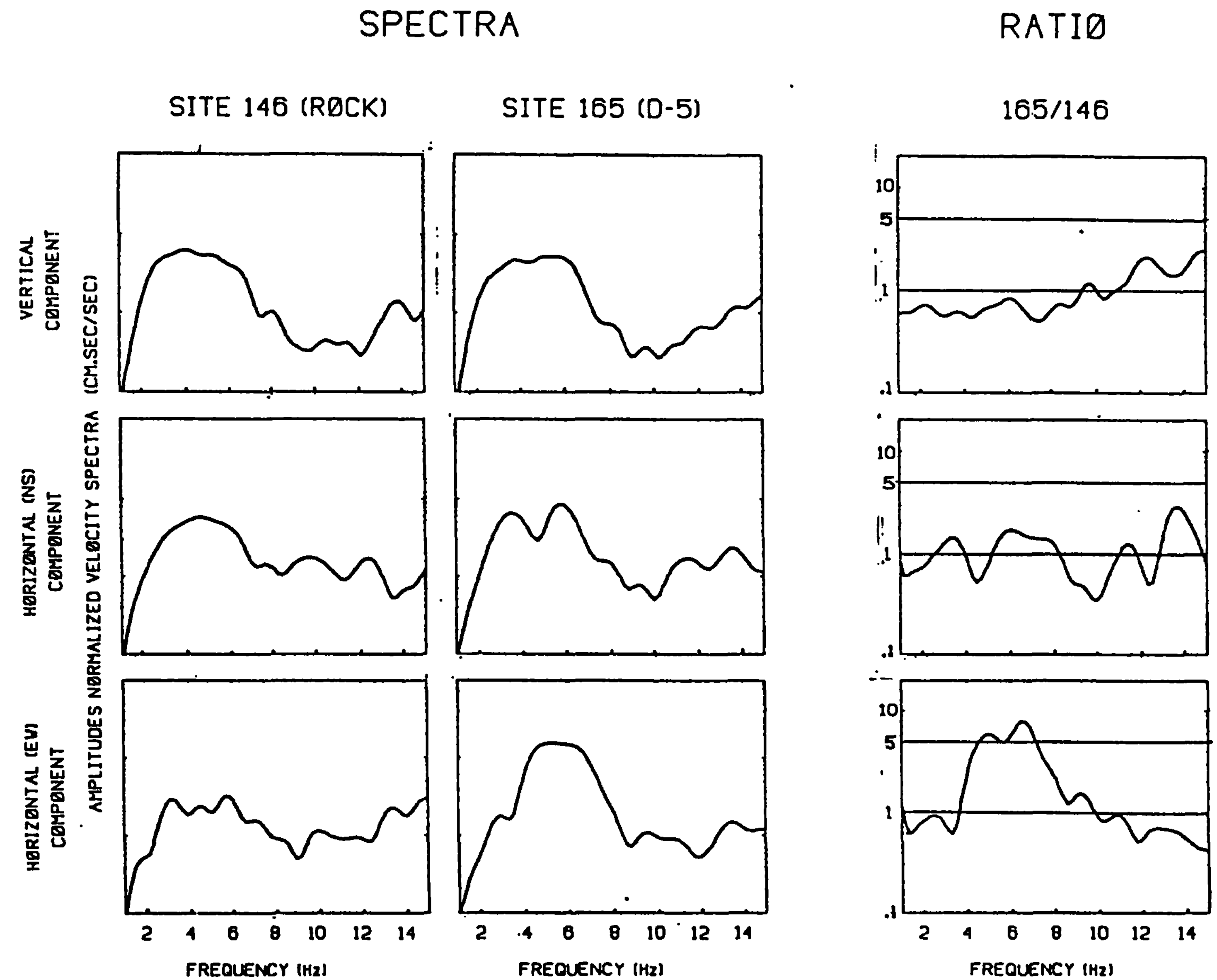


Figure 13.--Compared to site 146, site 165 also shows amplification of ground motion. The strongest amplification occurs in the east-west component.

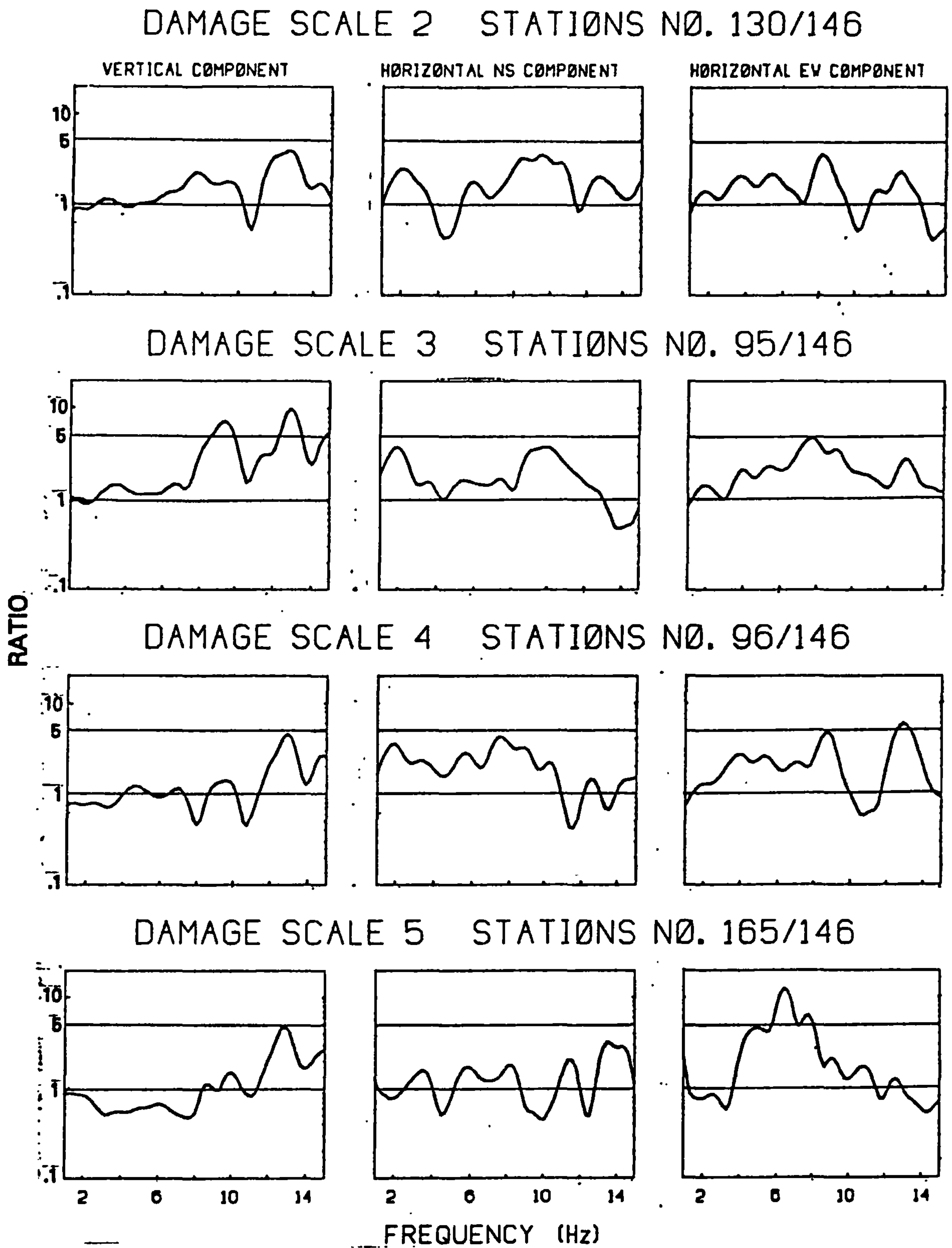


Figure 14.--Comparisons (ratios) of the spectra between the rock site and several other sites in the village. The damage scale rating is also indicated for that site.

and Rs is the distance of the standard site from the source. Solving the equation to normalize the ground motions at sites 130, 96, and 95 to the rock site yields factors (Ac/As) of 1.4, 1.4, and 1.6 for the vertical component and 1.2, 1.2, and 1.4 for the horizontal component ground motion (factors are greater than the ground motion at the rock site as the sites are 500, 600, and 800 feet closer, respectively, to the source than the standard rock site). The actual factors (AF) from the recorded data derived by dividing the rock-site velocity spectra into the comparison-sites velocity spectra are: 4.3, 4.9, and 9.2 for the vertical component and 4.1, 6.1, and 5.0 for the horizontal component, respectively. The approximate site response at these three sites can be closely estimated by the general formula: Af - Nf = SR , where Af is the rock to site factor from recorded data, Nf is the derived rock to site factor from the attenuation or predicted site ground motion, and SR is the site responses at that particular site. The site response for these three sites are approximately 3, 5, and 4 in the horizontal component, respectively. Site 166 which is approximately 400 feet (122 m) farther from the test explosion than the standard rock site has a scaled ground-motion factor of 0.8 to the standard rock site in the vertical component and 0.9 factor in the horizontal component as compared to the actual recorded ground-motion factors (AF) of 5 in the vertical component and 11.1 in the horizontal component. The comparison of these factors will give a peak site response at site 166 of 6 in the vertical component and 12 in the horizontal component.

A comparison of spectral ratios was made among the seismic recording sites in the village and a low damage rated (degree 2) site that is closer to the source (2,150 feet; 655.3 m) than the other sites investigated. Spectral ratios at all sites compared show equal or higher ground motions at selected frequencies in the 1-15 Hz band than were recorded at the low damage-close site (figs. 15 and 16). The comparisons also show that the site response amplifications of the ground motions are frequency dependent; that is, selected frequencies show increased ground amplification factors compared with the close-in site. For example: site 34 shows a factor of 5.9 amplification at 3.8-4.1 Hz in the east-west horizontal component, whereas the factor should be only 0.8 based on the attenuation function only. The 1.6 amplification at 12.5 Hz is a more critical factor since the natural frequency of the building at that site is approximately 12.2 Hz (table 2). A direct comparison of the ratio factors and the predicted numbers based on the attenuation functions are shown in table 5.

Table 5.--Predicted versus actual peak ground motion

| Site no. | Pred.V fact. | Actual fact. | Peak Hz | Pred.H fact. | Actual fact. | Peak Hz |
|---|---|---|---|---|---|---|
| 68 | .89 | 3.6 | 8.2 | .93 | 7.2 | 9.3 |
| 113 | .51 | 1.6 | 11.0 | .66 | 2.1 | 12.4 |
| 34 | .69 | 2.1 | 9.8 | .80 | 5.9 | 3.5 |
| 22 | .78 | -- | -- | .86 | 2.1 | 12.2 |
| 202 | .88 | .86 | 3.0 | .89 | 3.8 | 10.5 |
| 165 | .25 | 1.8 | 10.6 | .43 | 2.0 | 4.2 |
| 166 | .22 | 2.0 | 11.0 | .39 | 4.9 | 13.5 |
| 167 | .22 | 1.4 | 3.2 | .39 | 4.9 | 3.6 |

The structural response data of two buildings (165 and 167) were obtained by installing a portable seismograph system on the top of a bearing wall of the buildings and another seismograph system approximately one building height from the base of the buildings. The systems then recorded the ground and structural motions from the induced ground motions from one of the test explosion events. The test was made to obtain the structure-transfer function of the bearing walls of the buildings. The transfer functions or spectral ratios of the buildings were calculated in a similar manner to the transfer function for the various site conditions (top of bearing wall spectra/ground

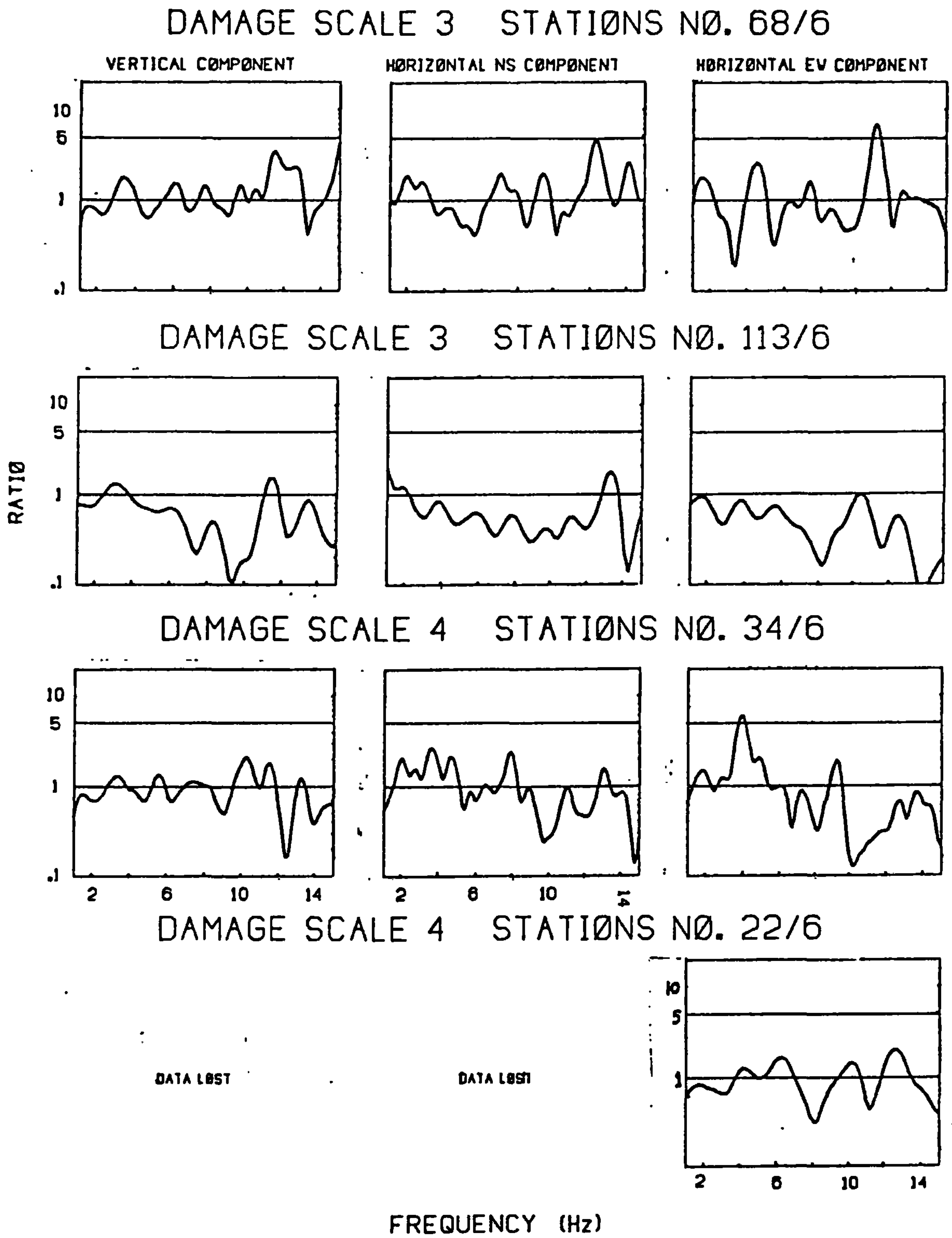


Figure 15.--A comparison of the spectral ratios for all three components between several sites and site 6 - a low damage rated site (grade 2)- which is closer to the test explosions than the sites to which it is compared. The ratios show equal or higher ground motion at selected frequencies in the 1 to 15 Hz band than were recorded at site 6.

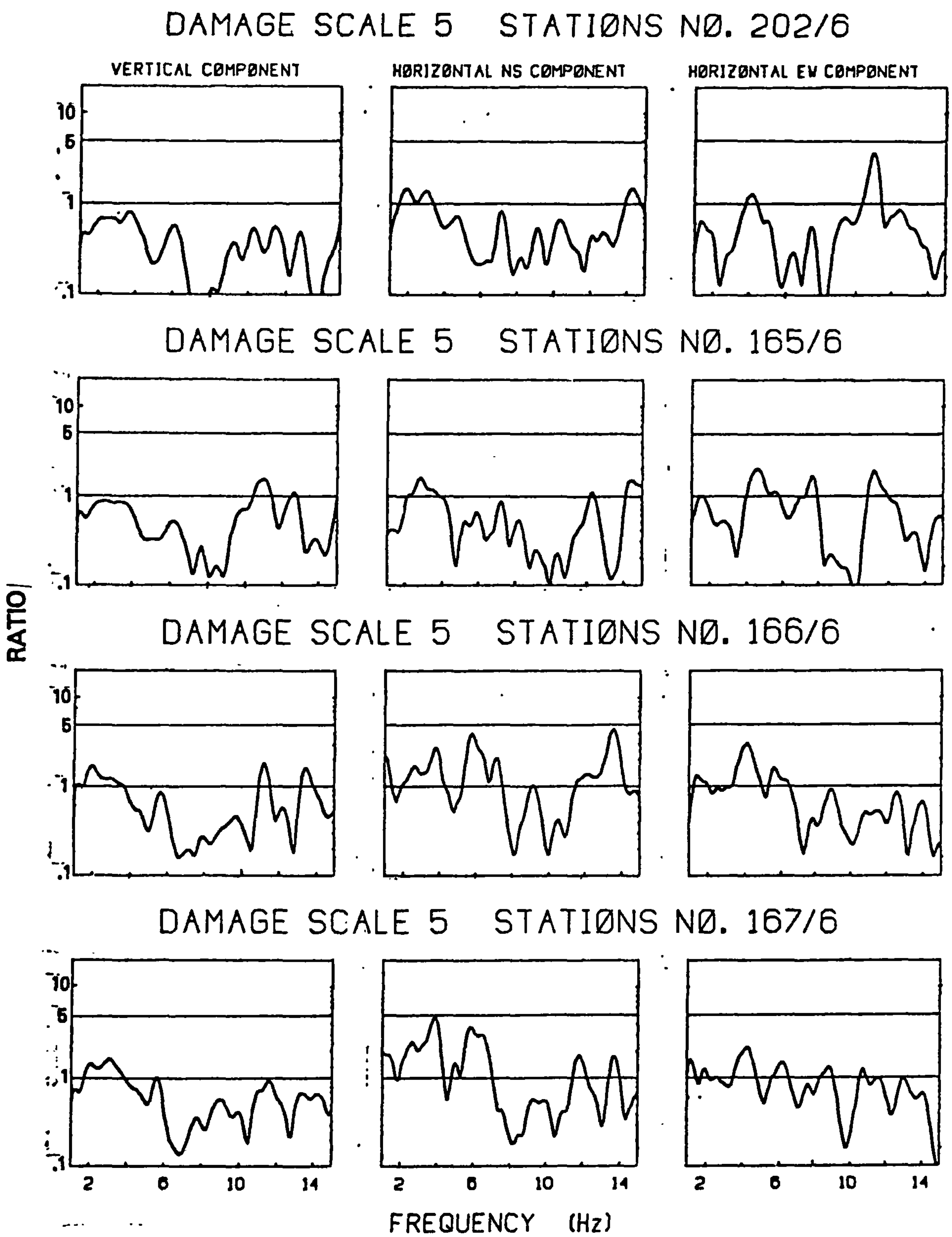


Figure 16.--Spectral ratio comparison for all three components between site 6 and several sites with a damage rating of 5.

spectra). The ground motion frequencies that are amplified by the structural response depend on the natural frequencies of the structure and the coupling of the building to the ground (Tschebotarioff, 1951). The spectral ratios of the induced motions show that building 165 will amplify most input frequencies between approximately 6-14 Hz with a peak amplification of 5.1 at 11 Hz in the north-south horizontal component and a factor of 3.2 at 9.2 Hz in the east-west horizontal component. Building 167 will amplify frequencies from approximately 6-11 Hz in the east-west horizontal component with a peak amplification of 6.5 for the frequencies from 9-11 Hz in the east-west component (fig. 17).

## DISCUSSION

The damage survey in the village of Paguate shows an overall intensity pattern that is irregular in areal distribution and is not related to distance from the Jackpile open-pit mine. The most heavily damaged structures are generally located in clusters of buildings which are located farther from the mine than are lesser-damaged structures. The main parameters that might contribute to or may be the cause of the observed damage to the buildings in the village are: shrinkage of building materials, thermal and moisture-activated expansion and contraction of building materials, construction methods (poorly constructed lintels, vigas, bond beams, etc.), differential compaction under the foundations, and/or vibration damage.

Cracks in a mud or adobe veneer-over-rock ("Chaco") type which are due to shrinking or drying of material will generally form a partial or complete polygonal pattern, will generally be small in width so as to account for the volume contraction of the material, and will not continue through a second medium (rock or wood). Poor design and/or construction of the type of

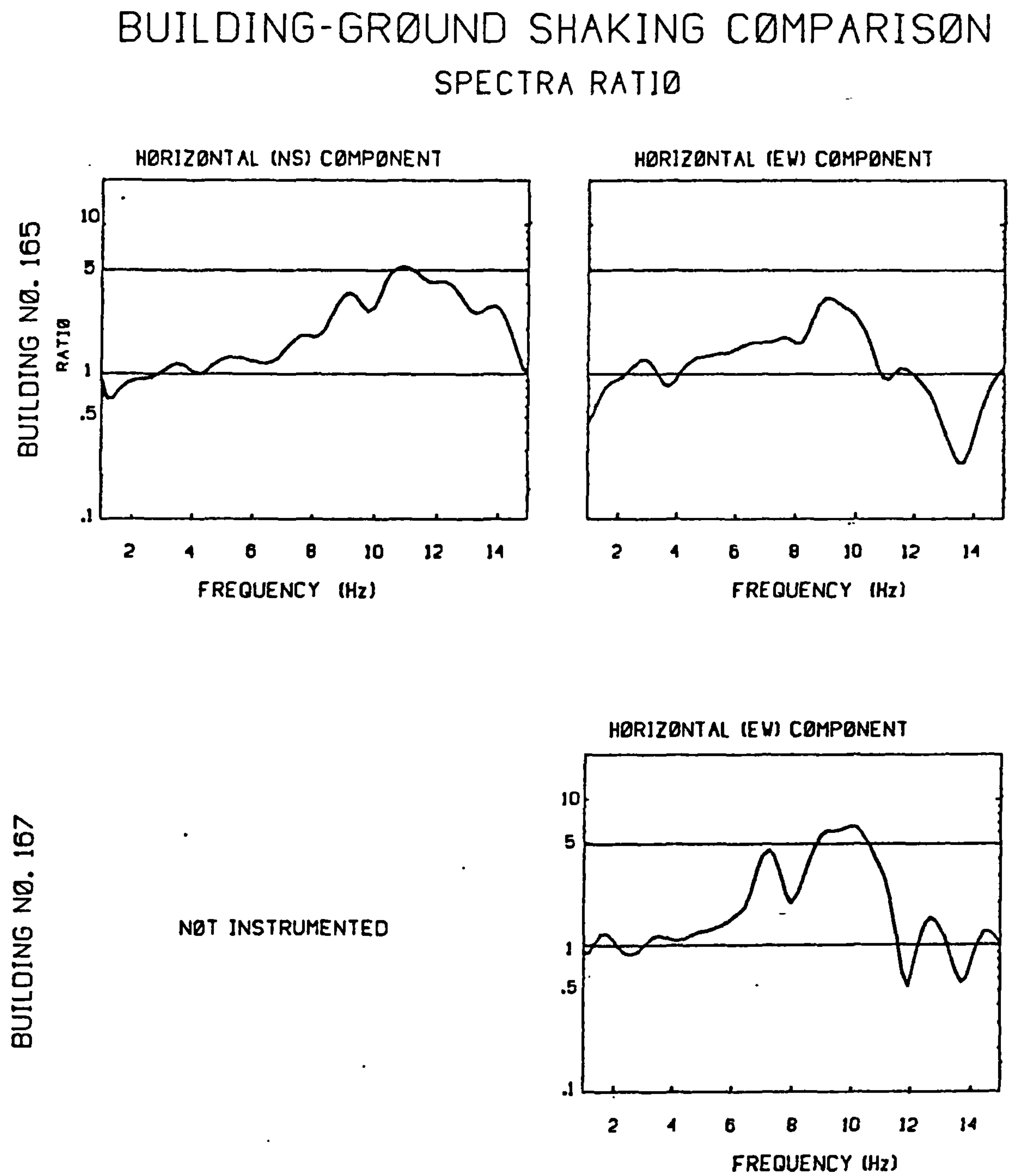


Figure 17.--The spectra for sites 165 and 167 were ratioed against the ground motion spectra measured one building height from the base of the building. Ratios show the frequencies that are amplified by the structural response of the building.

buildings in Paguate will usually show damage near the soil-building base interface (poor foundation and/or capillary action of moisture into the adobe), will show a separation of bearing walls with the largest separation near the top with the separation diminishing toward the bottom (poor bond beams) and similar obvious construction flaws. Shrinkage and construction damage was not considered when that could be identified. The buildings surveyed for degree of damage in the different villages were similar in construction and materials; therefore, the differences in the damage pattern in Paguate compared to the villages of San Felipe and Santo Domingo are probably due to differential compaction beneath the building foundations and/or vibration damage from ground motion.

The majority of the buildings in the most densely concentrated group of buildings in Paguate (south-central and northwest areas) have foundations that are directly on bedrock or are underlain by 1-2 feet (<1 m) of compacted sand/clay soil on top of bedrock. Differential compaction could not be a factor in the damage to these buildings. The buildings in the northwest section are underlain by approximately 5-8 feet (1.5-2.5 m) of unconsolidated sediments that overlay 5-8 feet (1.5-2.5 m) of low wave-velocity bedrock (weathered sandstone). The void ratios, the sand/clay mix, the exumed foundations, and the damage cracks that do not extend into the foundations do not suggest differential compaction as the cause of the observable damage. However, differential compaction can not be discounted as a contributing damage factor for the buildings located on the deeper sediments in the southwest area of the village. The data from the borings and refraction surveys in the southwest area did not reveal any present or historical changes in the water table. The lowering of the water table may cause a change in the pore pressure of the underlying sediments and thereby contribute to an increase or decrease of differential compaction under the foundations of a few of the buildings located in the area of thicker unconsolidated sediments in the southwest part of the town. However, observable evidence of compaction such as depressions, sinkholes, or sag areas are not present which indicates that the forcing mechanism for the compaction would depend on the weight distribution of the buildings which is relatively small due to the small size of the buildings and the thickness of the bearing walls. All of the buildings are one-story, "Chaco", frame-mixed type structures with rock footings.

The site and building response studies clearly show that ground motions in the 1-15 Hz frequency band at selected frequencies are larger in areas that are farther from the mine, but are underlain by greater thickness of unconsolidated materials than areas that are closer, and that the measured site response correlates well with the degree of building damage. An average site amplification of ground shaking of 5 at frequencies between 1-15 Hz was found for the sites underlain by unconsolidated sediments. Site 165 has a site-amplification factor of 11 at 6 Hz. These amplification factors indicate that the ground motions predicted by normal attenuation-scaling methods must be multiplied by factors from 5 to 11 for selected frequencies. The comparison of the high response areas with the standard site that was up to 2.2 times closer to the blasts show that the high response areas further from the blast receive as much or more blast-induced ground motion than the closer sites at selected frequencies. The data also show that the natural periods of the buildings coincide with the amplified site-response frequencies. The building-response study showed that on the two buildings tested, the building response amplified the natural frequencies of the buildings by factors from 3.2 to 6.4.

The high mass, low structure stiffness, and high natural frequencies of the rock-adobe buildings in Paguate results in the buildings having a high susceptibility to damage from blast-induced ground motions. The general frequency band for induced ground motions from the test blasts is 1-15 Hz. The natural frequencies for the buildings range from 3-15 Hz with the mode concentrated at approximately 10-12 Hz. The added construction and repairs which were made to the buildings during the past 15 years do not seem to have retarded the damage to the buildings. The added stucco layers tend to cover the existing cracking; however, in most cases the cracking can be followed through the rock core to the interior of the building or the damage (cracks) have reopened through the stucco. The buttresses that have been added to the buildings (such as at buildings 165 and 167) may slow differential compaction or support the weight of the walls which is what they are designed for in the "Spanish" type of adobe construction (O'Connor, 1973). The buttresses added to the buildings in Paguate have, in general, increased the buildings coupling to the ground and shortened the effective heights of the walls. The shorter walls have a higher natural frequency which is also in the bandwidth of the that source. The buttresses may have increased the sensitivity of the building to the ground motions in the frequency band most damaging to the buildings. Detuning or changing the natural frequency of the buildings away from the peak frequencies induced by the blasts would probably help miniminize the damage from the induced motions. In general, most of the repairs that can be observed did not either detune the buildings or strengthen the bearing walls.

The cumulative effects of the induced ground motions on the buildings could not be evaluated. The adobe and rock construction is less elastic than the average cement-block or stick-frame building. Once damaged or cracked, the adobe material used for surfacing the rock core walls and the filler in the rock cores will not "heal" or return to its original state (Clifton, 1979). The cumulative effect of the over 1,400 blasts which took place at the quarry could be significant; however, due to the lack of proper historic documentation and the limited scope of this investigation, the effects can not be evaluated.

The blast durations will vary with the length of the row type charges and the 0 to 9 ms shot delays the mining company used in their operations (Department of Interior, 1984). Duration of ground shaking has been shown to be one of the more important parameters in the destructive capabilities of ground shaking (Hays and others, 1978). The data from the single test blasts show that the induced horizontal shaking at site 6 (low damage at 2,200-foot; 670 m range from the shot) and at site 165 (high damage at 4,400-foot; 1,341 m) range) will last approximately 1.5-2.6 seconds, respectively.

Comprehensive damage-ground motion studies by Trifunac and Brandy (1975) and Trifunac and Westermo (1977) have provided evidence that three interrelated parameters: the amplitude level, the duration that the ground shakes, and the frequency that the ground shakes are the important parameters that cause structural damage. The data results from the Paguate investigation show: (a) sites that have high site response and have higher ground motions at greater distances from the source than sites located on or close to bedrock, (b) sites not on bedrock have amplification factors of 5 to 11, (c) a test sample of the building amplifications show building amplifications of 3 to 6, and (d) increased duration of ground motion at areas of concern. These data and results are not unique. Several earthquake, blast, and building studies have shown similar results (Algermissen and others, 1972, 1973;

Borcherdt and others, 1970, 1976; Hays and others, 1978, 1982; Rogers and others, 1980, 1978, 1979; King and others, 1986; Steinbrugge, 1981).

## CONCLUSIONS AND RECOMMENDATIONS

The seismic data analysis from the Paguate investigation show : (a) sites at greater distances from the source than many buildings in the village have larger and longer duration shaking at several frequencies due to the site ground motion response, (b) the buildings' structural response to the induced ground shaking is within the site-response bandwidth, (c) there is no clear evidence of differential compaction under the foundations of the building at most of the sites, (d) the vertical ground-motion attenuation function used by many investigators and mining companies ($R^{-1.6}$) is suitable for vertical ground motion attenuation for sites on rock in the Paguate area, (e) the peak horizontal ground motion in the Paguate area attenuates as $R^{-1.15}$. The analysis of the test shots, building studies and soil tests strongly suggest that the damage to the buildings in the high response areas was greatly augmented or caused by the vibrations induced from the mine blasting. The damage in the buildings in the scale-3 grading were probably largely caused or increased by the quarry blasting. The cause of the scale-2 graded damage could not be clearly identified but it is reasonable to assume that blasting at least contributed to the damage.

The following are recommendations for future blasting for mining, reclamation, and/or industrial development.

1. The induced vertical and horizontal ground motions should be monitored at a minimum of at least three sites during blasting operations. Recommended sites are 165, 146, and 202. Monitoring at six sites would be very desirable (buildings 6, 34, 165, 146, 202, China Town). Pre-event

inspections should be made of approximately 20 significant structures (sites 6, 20, 21, 34, 50, 71, 96, 99, 144, 148, 164, 167, 168, 202, 220, 221, 300, 304 and China Town are suggested). If no new damage has occurred at the selected buildings and preliminary analysis of the seismic data indicates the ground motion at site 165 has not exceeded approximately 0.1 inches/s (2.54 mm/s), the yield of the blasts could be increased until the ground-motion limits are reached. This testing will establish the maximum yield and shot configuration for any particular operation.

2. Test blasts should be set off and monitored before commencing routine blasting operations. It is recommended that the maximum ground-motion velocity at site 165 not exceed 0.1 inches/s (2.5 mm/s). It is also recommended that an attenuation scaling function of $R^{-1.1}$ be used for horizontal ground motion. The induced vertical and horizontal ground motions should be monitored at a minimum of three sites during blasting operation.

3. Changing the natural frequencies of the buildings that are more sensitive to the induced ground-motion frequencies should be attempted where practicable.

4. Do not add more stiffening to the buildings unless the induced source frequencies and the natural frequencies of the buildings are taken into account.

5. Run the blasting operations only when the wind is blowing away from the village to avoid both the overpressures on the flat-roofed houses and to minimize the personnel-disturbing acoustics that usually accompany surface or wall blasting.

6. Any repairs to the buildings should be made using native materials and with consideration of the natural frequencies of the structure. The owners should understand that newer construction methods will probably require different foundations and an engineered coupling method to integrate the older construction to the new construction.

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